ENERGY SPECTRUMS FOR PROTON (200 eV $\leqslant$ E $\leqslant$ 1 MeV) INTENSITIES IN THE OUTER RADIATION ZONE*

by

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The directional, differential spectrums of proton intensities mirroring near the magnetic equator in the outer radiation zone are obtained for the energy range 200 eV $\leqslant$ E $\leqslant$ 1 MeV with measurements from the spacecrafts OGO 3, Explorers 12 and 14 and Mariner 4. Several implications of these observational results with respect to current magnetospheric models of diffusion and acceleration mechanisms are discussed.

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Over the past several years *in situ* observations of the charged particle distributions within the earth's outer radiation zone have established the existence of large intensities of protons within the energy range 200 eV $\leq$ E $\leq$ 1 MeV in this region. This proton distribution has been surveyed for the most part by two instruments. A scintillator-photomultiplier instrument flown by Davis on Explorers 12 and 14 [Davis and Williamson, 1963, 1966; Davis, 1965] yielded early measurements of the proton intensities within the energy range 100 keV $\leq$ E $\leq$ 1 MeV. These observations provided the impetus for advancing radial diffusion models for acceleration of energetic outer-zone protons [cf. Dungey, *et al*, 1965; Nakada and Mead, 1965; Nakada, *et al*, 1965; Hess, 1966]. An extensive critique of the relationship of these proton intensities with those observed at higher energies, E $\geq$ 1 MeV, has been given by Hess [1968]. Later the intensities of lower-energy protons, 200 eV $\leq$ E $\leq$ 50 keV, were surveyed with a sensitive electrostatic analyzer array flown on OGO 3 [Frank, 1967b, 1970b; Swisher and Frank, 1968; Frank and Owens, 1970]. These lower-energy proton distributions within the outer radiation zone are responsible in large part for the distortion of the distant magnetosphere by virtue of their relatively large energy densities and are fundamental to an eventual understanding of auroral and magnetotail phenomena. Enhancements of these proton intensities, i.e., of the extraterrestrial ring current, are mainly responsible for the decreases of magnetic field intensities measured at the earth's equator during main-phase geomagnetic storms.

Our present interest is directed toward demonstrating that both the high- and low-energy proton distributions measured by the two aforementioned instruments are in fact the same proton distribution, i.e., the Explorer 12 and 14 observations of proton intensities at 100 keV $\leq E \leq$ 1 MeV are measurements of the high-energy 'tail' of the ring-current proton spectrums measured with OGO 3 over $4.5 \leq L \leq 6.0$ R_E (R_E, earth radii). To our knowledge only one attempt at comparing these two series of observations has been published [Frank, 1967a]. This comparison was presented for two <u>individual</u> measurements differing significantly in both year of measurement and local time; no viable functional fit to the entire energy spectrum was, or could be, offered on the basis of such limited observations.

Two exemplary proton differential energy spectrums within the extraterrestrial ring current for a period of relative magnetic quiescence on 1 July 1966 are presented in Figure 1. The instrument measured protons mirroring within 15° of the magnetic equator. Characteristics of these <u>individual</u> observations of present interest are (1) a maximum of differential intensities at $\sim$ 10 keV and (2) smoothly declining differential intensities over the energy range extending from $\sim$ 10 keV through the lower energy range to $\sim$ 200 eV. Individual observations such as those presented in Figure 1 demonstrate the general character of the proton spectrums within the extraterrestrial ring current; however, due to large temporal fluctuations of intensities [cf. Frank, 1967b] it is necessary to obtain average energy spectrums for an extended period of observations in order to compare these observations with those of higher energy protons with Explorers 12 and 14. The average differential energy spectrums of proton intensities over the energy range 500 eV $\leqslant$ E $\leqslant$ 50 keV for an extended period of observations during June through July 1966 were obtained from the published survey of these proton intensities by Frank and Owens [1970]. Measurements during the periods of two moderate main-phase magnetic storms were not included. The results of this averaging for L = 4.5, 5.0 and 6.0 are summarized in Figure 2. The units for the ordinate scale for all observations shown in Figure 2 are directional, differential proton intensities at equatorial pitch angles $\alpha_o = 90°(\pm 10°)$.

The observations of intensities of higher energy protons 100 keV $\leqslant$ E $\leqslant$ 1 MeV as given by Davis [cf. Nakada and Mead, 1965] at L = 4.5, 5.0 and 6.0 and with equatorial pitch angles $\alpha_o = 90°$ are also summarized in Figure 2. These measurements were gained with an instrument measuring directional, integral intensities. Hence, in order to convert the integral intensities to corresponding differential intensities, we have subtracted corresponding integral intensities for adjacent energy thresholds of the instrument and have divided these intensity differences by the energy range, in eV, between the adjacent energy thresholds. The horizontal bars for the Explorer 12 observations as shown in Figure 2 are coincident with these energy ranges. For comparison with these results we have included two measurements with a surface barrier detector flown on Mariner 4 [Krimigis and Armstrong, 1966] for the proton spectrums at $L = 4.5$ and $L = 5.0$. These _differential_ intensities were calculated from observations of integral intensities via the aforementioned method. We judge that the conversion of all these measurements to a homogeneous set of units, i.e., protons $(cm^2\text{-sec-sr-eV})^{-1}$, is accurate to $\sim 30\%$. The largest errors, almost impossible to evaluate, may possibly arise from the disparity among the periods of measurements: Explorer 12 (1961), Mariner 4 (1964) and OGO 3 (1966). However, the overall agreement among these three series of observations as summarized in Figure 2 is indicative of no severe differences in _average_ proton intensities, i.e., by factors $\geqslant 2$ or 3, for these periods of observations [cf. Davis and Williamson, 1966]. Simultaneous observations of the proton spectrums over the entire energy range $200 \text{ eV} \leqslant E \leqslant 1 \text{ MeV}$ would be obviously worthwhile in critically examining this conclusion.

We have examined several simple functions, including power laws and exponentials, with the intent to conveniently summarize the present observations of differential spectrums of proton intensities over the energy range 200 eV $\leqslant$ E $\leqslant$ 1 MeV and find that the directional, differential proton spectrums can be approximated with reasonable accuracy by

$$\frac{dJ}{dE} = K \sqrt{\frac{E}{E_*}} \exp\left(- \sqrt{\frac{E}{E_*}}\right)$$

where $\frac{dJ}{dE}$ is the directional, differential intensity of protons mirroring at the magnetic equator and K and E_* are functions of shell parameter L. Values for E_* which most accurately reproduce the differential energy spectrums for the observations at L = 4.5, 5.0 and 6.0 shown in Figure 2 are 8.0, 6.0 and 3.5 keV, respectively. E_* increases with decreasing values of shell parameter L. The dashed lines are the corresponding calculated spectrums. It should be noted here that Davis [1965] has invoked an exponential function as a best fit to the Explorer observations of directional, <u>integral</u> proton intensities mirroring at the magnetic equator, i.e.,

$$J(>E) = C \exp\left(- \frac{E}{E_o}\right)$$

where J(>E) is the directional, integral intensity of protons with energy greater than E and C and E_o are functions of shell parameter L. Typical values for E_o at L = 4.5 and 6.0

are 150 keV and 60 keV, respectively. This exponential fit cannot qualitatively reproduce the present observational result of decreasing differential intensities with decreasing energy for proton energies $\leqslant$ 5 keV (cf. Figures 1 and 2).

The overall continuous character of the proton spectrums over the entire energy range 200 eV $\leqslant$ E $\leqslant$ 1 MeV, i.e., a broad proton spectrum with a single maximum of differential intensities at 5 to 10 keV and monotone decreasing intensities with lower and higher proton energy, appears to indicate that this entire proton distribution is related via a common source and/or acceleration mechanism(s). Hence any proposed model or mechanism forwarded to account for this proton distribution, such as radial diffusion inward from a more distant region of the magnetosphere [cf. Nakada, et al, 1965; Dungey, et al, 1965] or acceleration of exospheric ions via stochastic resonance interactions with electromagnetic radiation [cf. Pizzella, 1970; Pizzella, et al, 1970], should contend with details of the entire proton distribution over the energy range 200 eV $\leqslant$ E $\leqslant$ 1 MeV. With regard to radial diffusion models for acceleration of outer zone protons we note (1) the general character of the proton spectrums shown in Figure 2 relating the extraterrestrial ring-current proton spectrums with the higher energy proton spectrum, $E \geqslant 100$ keV, observed by Davis and (2) the current evidences strongly implying that the ring-current and plasma sheet proton distributions beyond $L \simeq 6.5$ are the signatures, at least in part, of large-scale magnetospheric convection [cf. Axford, 1969; Brice, 1967; Frank, 1970a, b]. On the basis of the above comments we suggest that the appropriate source (boundary) region for models of radial diffusion of protons into the outer radiation zone is not located at the magnetopause as previously suggested [cf. Nakada, et al, 1965; Hess, 1968] but in the vicinity of the earthward edge of the quiet-time extraterrestrial ring current at $L \simeq 6.5\ R_E$.

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Figure Captions

Figure 1. Directional, differential energy spectrums of proton intensities within the extraterrestrial ring current at L = 5.35 and 5.71 at low magnetic latitudes on 1 July 1966. These protons were observed at local pitch angles, α_d (dipole field), with mirror points within 15° of the magnetic equator. The calculated dipole field, B_d, at the position of the spacecraft OGO-3 is also given for each L-value.

Figure 2. Directional, differential spectrums of proton intensities over the energy range 200 eV $\leqslant E \leqslant$ 1 MeV and mirroring at the magnetic equator as compiled from observations with OGO 3 [Frank and Owens, 1970], Explorer 12 [Davis and Williamson, 1966] and Mariner 4 [Krimigis and Armstrong, 1966]. The ordinate scales for the proton spectrums at L = 4.5, 5.0 and 6.0 have been displaced by factors of 10 as noted on the

Figure 2. (cont.)

left-hand ordinate scale, i.e., maximum differential intensities are $\sim 10^3$ protons $(cm^2\text{-sec-sr-eV})^{-1}$ at ~ 10 keV for each spectrum. The horizontal bars for each measurement indicate the effective energy bandpasses of the instruments. These observed proton spectrums can be approximated with reasonable accuracy over the entire energy range by the function

$$\frac{dJ}{dE} \alpha \sqrt{\frac{E}{E_*}} \exp\left[-\sqrt{\frac{E}{E_*}}\right]$$

(see text). Appropriate values for E_* are 8.0, 6.0 and 3.5 keV at L = 4.5, 5.0 and 6.0, respectively.

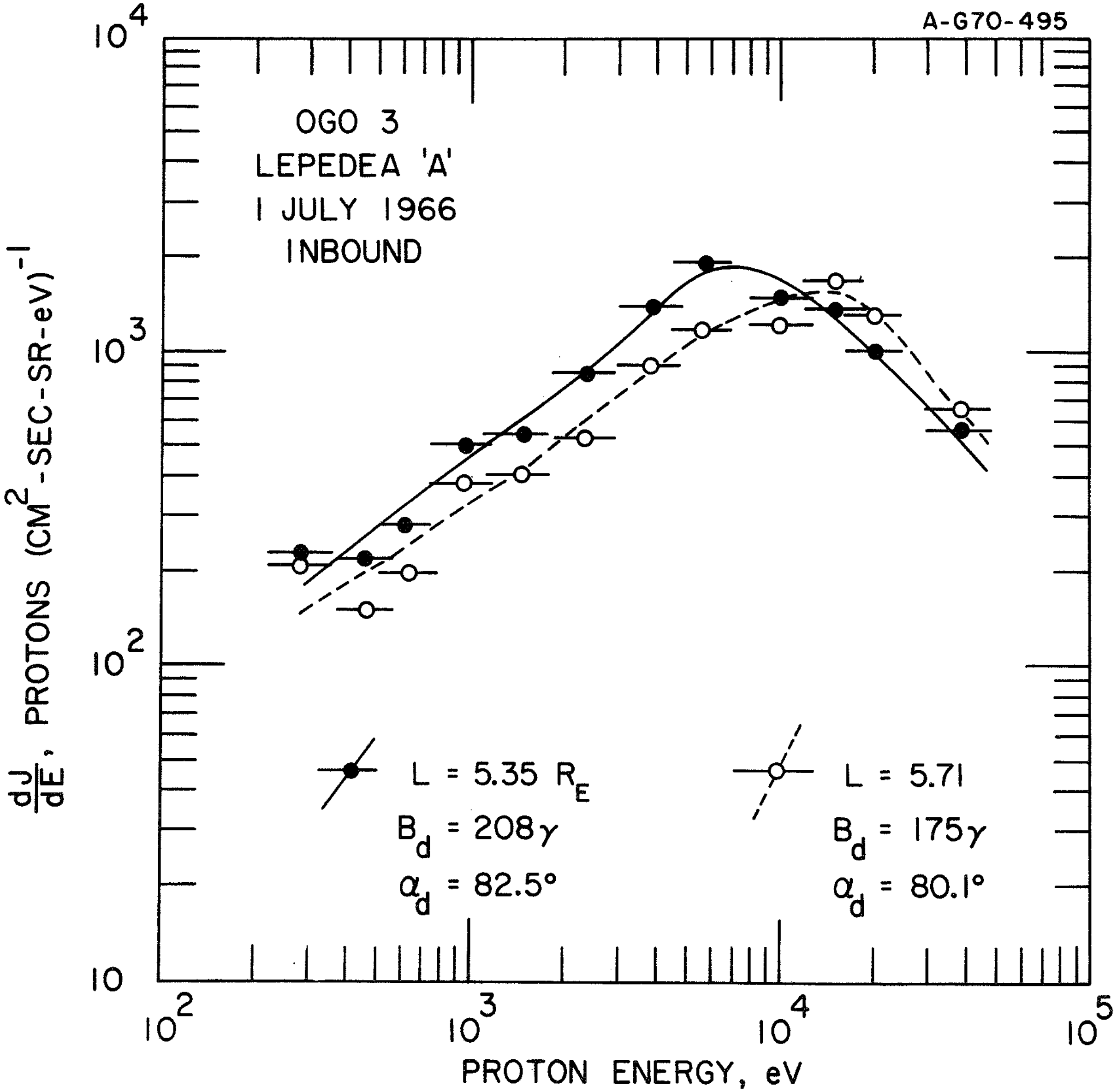
A-G70-495
OGO 3
LEPEDEA 'A'
1 JULY 1966
INBOUND
L = 5.35 R_E
B_d = 208γ
α_d = 82.5°
L = 5.71
B_d = 175γ
α_d = 80.1°
dJ/dE, PROTONS (CM^2-SEC-SR-eV)^-1
PROTON ENERGY, eV
10^4
10^3
10^2
10
10^2
10^3
10^4
10^5

Figure 1

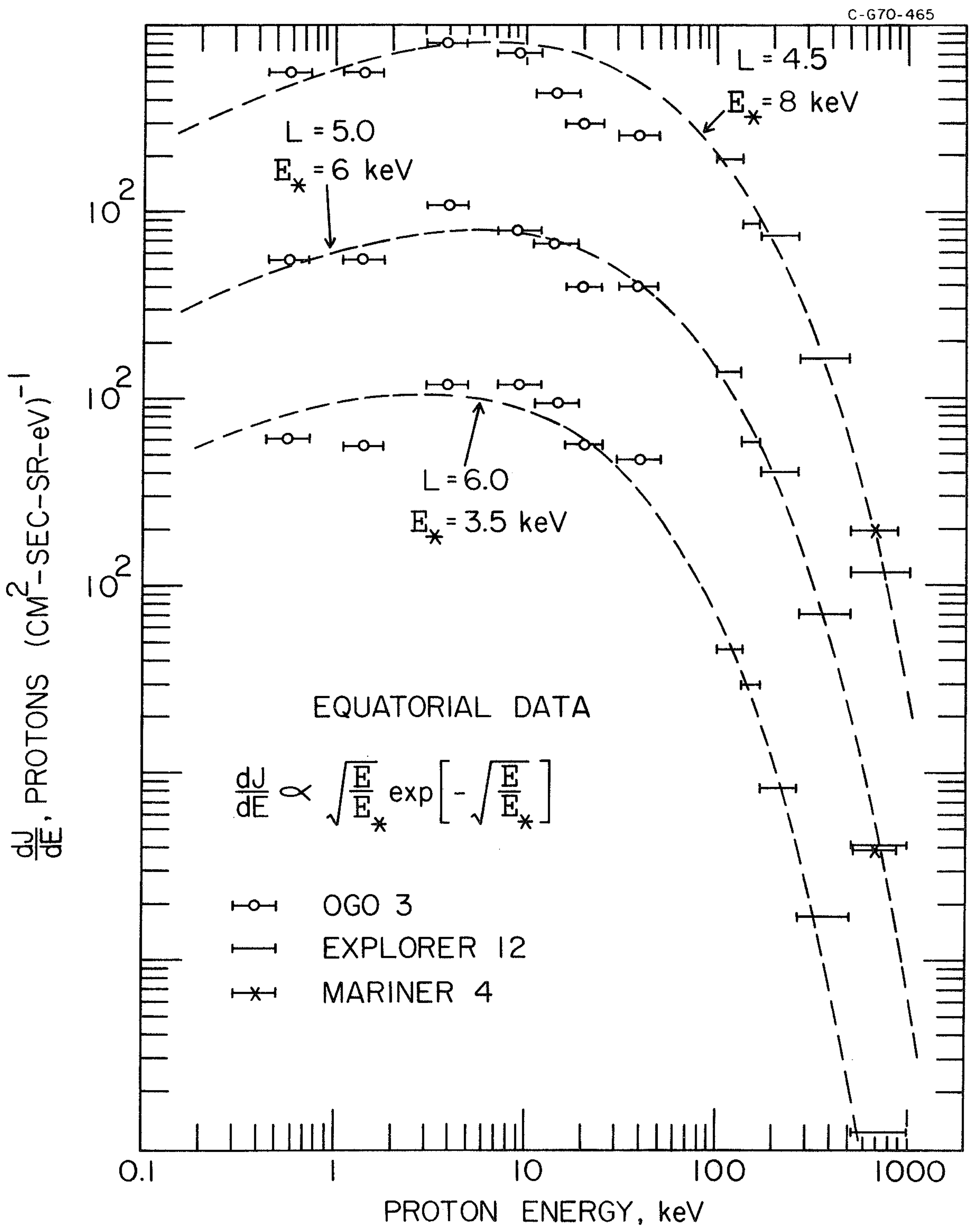
C-G70-465
L = 4.5
$E_* = 8$ keV
L = 5.0
$E_* = 6$ keV
L = 6.0
$E_* = 3.5$ keV
10^2
10^2
10^2
$\frac{dJ}{dE}$, PROTONS $(CM^2\text{-SEC-SR-eV})^{-1}$
EQUATORIAL DATA
$\frac{dJ}{dE} \propto \sqrt{\frac{E}{E_*}} \exp\left[-\sqrt{\frac{E}{E_*}}\right]$
OGO 3
EXPLORER 12
MARINER 4
0.1
1
10
100
1000
PROTON ENERGY, keV

Figure 2